# Solar Powered AUVs; Sampling Systems for the 21st Century

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## LONG-TERM GOALS

The long-term goal of this program is to investigate those technologies that will enable the use of solar energy to power Autonomous Underwater Vehicles (AUVs). The program will focus on investigation of our ability to extract sufficient energy from the sun's radiation to power an AUV and our ability to efficiently manage the collection, storage, and utilization of that energy such that an AUV is able to perform tasks required during a mission. It is expected that, at the conclusion of this phase of the program, we will understand not only the relevant technologies, but also the advantages, methods of implementation, and limitations of their use on solar AUVs (SAUV). Research into integrating new as well as existing communication capability among distributed vehicle platforms and users.

## OBJECTIVES

Maximize the potential mission length of SAUVs by optimization of the energy extraction from PV Solar panels using low power consumption electronics and intelligent battery charging techniques. Characterize and optimize SAUV hull design with respect to reducing drag resistance, improving stability, and maximizing propulsion efficiency. Integrate GPS navigation and RF communications systems into the SAUV and link these systems to an interactive AUV computer simulation environment currently under development at the Autonomous Undersea Systems Institute (AUSI).

## APPROACH

Conduct research of existing solar energy components, their usefulness and potential for application in an integrated system for AUVs. Conduct experiments to acquire data and assess the extent to which solar energy is viable as a power source for AUVs. This involves designing a solar energy system test bed to conduct laboratory experiments to specifically determine the efficiencies and limitations of subsystems composed of PV solar arrays, battery systems, charge monitors and charge controllers, etc., and to assess the degree of integration compatibility between the various electronic components. Use the solar energy test bed to investigate various power management strategies developed within this program. Design and fabricate a solar AUV platform for the purpose of carrying out in-water evaluations of energy collection under conditions of wave motion and water splashing over solar arrays. Develop software models of waves, platform, and energy system to serve as an evaluation and design tool and to conduct simulation experiments of various aspects of solar AUV systems. Design and fabricate a simple solar AUV prototype vehicle to conduct at sea tests of the first principles of solar powered AUVs.

## WORK COMPLETED/RESULTS

***At Sea Performance Testing of Solar AUV.*** Modernization of hardware control system to a 486-based microprocessor. Updated program control (software) implemented within QNX real-time operating system. Functional check, debugging and operational development of the vehicle devices and systems. A modified propeller to increase output power and increase overall thruster efficiency. Improvement of the hydrodynamic characteristics and comparison with previous empirical results. GPS efficiency investigation depending on sea state conditions. SAUV energy balance investigation.

*Results*. Research has concluded that Autonomous Undersea Vehicles, such as the SAUV, need an advanced computer system in order to take advantage of today's subsystem technologies. AUV subsystems such as navigation and communications are computationally intensive and produce a good deal of data. To incorporate them into an AUV and exploit their full capabilities they have to be part of a system that can service them in a timely fashion and record their data for future use(s).[1] A new hardware and software control system was installed and tested. The hardware is centered around SCE86406-03 by EPSON (486 16MHz 4M). Software is based on QNX's Real-Time Operating System (RTOS) and allows for a very robust implementation of the complex control algorithms needed for the SAUV. In order for the SAUV to maximize the mission time and capabilities, it was necessary to upgrade the battery packs. The SAUV should be able to acquire the maximum amount of energy it can from the sun's radiation. The old configuration had four batteries of six cells at 10AH for a total of 240 watt-hours of energy. Now the SAUV has two batteries of sixteen cells at 20AH for a total of 640 watt-hours of energy.

Since the majority of the total energy required for the SAUV goes to the propulsion subsystem, it was determined that the efficiency of the original propellor was low. Researching and installing a new propeller with a diameter of 173mm increased the Thruster power amplitude. The original propeller's diameter was 140mm. This resulted in an overall thruster efficiency increase of ~22%.[2]

| N rot/min | V m/s | Thrust W | Rudder/ Flap, W | Control System, Compass, Roll, Pitch, Depth Sensors, W | Total W |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 1.7 | 1.7 |
| 320 | 0.5 | 10.74 | 2.11 | 1.7 | 14.55 |
| 450 | 0.7 | 23.13 | 5.09 | 1.7 | 29.92 |

***Figure 1. SAUV systems energy consumption measurement***

By using a more precise experiment, the drag resistance coefficient was found to be lower than the original measured 0.17 - 0.18 rating. The new measurement is 0.12 to 0.13. Looking at equation 1-$c_{xv}$ is the drag coefficient and is equal to:

$$c_{xv} = \frac{P}{\frac{\rho}{2\eta}\upsilon^3 V^{2/3}} \qquad (1)$$

Where P is the power required for propulsion, ρ is water density, η is efficiency of motor and thruster, υ is the velocity of the SAUV, and V is the water displacement. As can be seen the lower the drag coefficient the lower the Power requirements. This signifies longer or more complex missions. It is hoped that in the near future the coefficient can be reduced to 0.08 - 0.10 with future additional modifications to the hull.

Global Positioning System (GPS) fix time on the open water has been measured. As can be seen Figure 2 that the GPS fix times vary according to the sea state. In calm water it takes approximately 20 seconds to acquire the fix. As the sea states become higher the amount of time to acquire the fix increases, up to 10 minutes. This could become a problem in a violent storm where it may be impossible to attain a reading. At present, this is not a major problem for the SAUV because off the shelf GPS systems typically require less than 1 watt to operate.

Sea trials were conducted May of 1999, Spring of 2000, and Fall of 2000 in Peter the Great Bay (near Vladivostok). Many runs have been executed with the objective of defining performance of the vehicle and verifying it's ability to function as a moving platform for long endurance measurements in the ocean. Also, the properties of vehicle behavior in conditions unique to the SAUV such as sea-keeping during drifting or moving on the surface were considered.[3] In addition to many minor problems being resolved during the trials, the SAUV batteries were recharged exclusively through the photovoltaic panels (PVP) using solar energy for four straight days - September 11th to the 14th. A total travel distance was 45,111 meters.

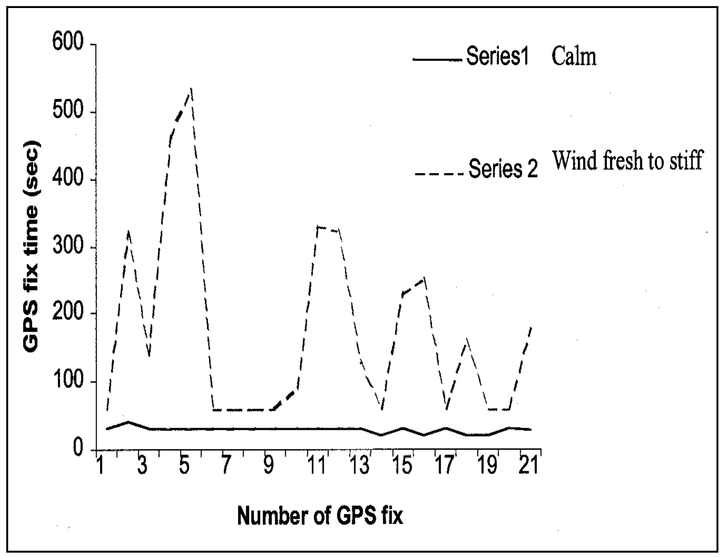


*Figure 2. GPS Fix Times*

***Solar Energy System Test Bed (EST).*** Exercise the EST situated in a remote water bound context, collect solar energy data, communicate with the platform over several unique communication links, and distribute that data in near real time to Visual clients over the Internet via the Cooperative AUV Development Concept (CADCON) communication harness.

*Results AUV Demo 99.* Principal components linked together during the demonstration included the EST platform, the research vessel, the shore station and CADCON elements. These components used links based on both Ethernet and serial protocols, radio frequency (RF) and cellular telephone modems, and the Internet. In addition to this, several PC-based applications were utilized, including an early version of the CADCON Autonomous System Monitoring and Control (ASMAC) client, as well as the AUVSim and Visual clients for remote representation and monitoring of the vehicle, respectively. By using this approach, insights were gained in networking representative Autonomous Ocean Sampling Network (AOSN) components. Additional insights gained were the understanding of issues related to public versus private access to vehicle control, communication time delays between nodes, impact of node failures upon both command and monitoring, and understanding general aspects of interfacing mature nodes with experimental nodes.

*Results Field Test Feb 2000*. The EST platform was transported to New Castle, NH for another set of remotely situated demonstrations. The focus of these experiments was to complete a series of validation tests started at the AUV Demo of a prototype satellite communication system called the Ocean Data Link (ODL), under development for ONR by ViaSat Corporation. ODL employs existing C-band geosynchronous satellites to provide two-way communications with full ocean coverage utilizing low power transceivers. An ODL transceiver prototype was mounted on the EST and was placed 5-10 m out in mild ocean surf off New Castle. The demonstration consisted of regular polling of the EST status and GPS information over the satellite data link using a modified AUVSim client. The EST/ODL equipment responded with appropriate energy status or GPS information. This information was then made available on the Internet through the CADCON Visual client.[4]

Roughly 75% of the messages that were transmitted over the data link were received correctly and processed. Originally it was considered to be quite acceptable given the prototype conditions. Subsequently, it was determined that the ODL and EST were improperly positioned during the demonstration and the satellite was not in the main beam of the antenna. After analyzing the test data, it was determined that there is considerable margin in the data link design.[5]

***Control Hardware Architecture Research.*** Research different distributed control implementations for SAUV. Compare current and future battery technologies.

*Results*. Traditional embedded system design employs a centralized control architecture, where a single computational unit is tied directly to all system sensors and effectors via customized IO channels. While this monolithic approach maximizes system efficiency in the area of energy consumption, it often generates systems, which are difficult to maintain and upgrade due to the abundance of customized IO channels. With AUVs, this situation incurs considerable cost with any effort to interface (or modify) scientific sensor packages to the vehicle body.

Modern embedded systems design is moving towards a more modular, re-configurable, and flexible control architecture: the internal control network. This leads to distributed control architectures that are modular in nature. This trend is evident in the AUV community as evidenced by vehicles developed at Florida Atlantic University (Ocean Explorer), Maridan Corp (Martin), and the University of South Hampton (Autosub). This type of architecture increases a vehicle's utility in terms of overall capability, flexibility, configurability, and lifetime before complete obsolescence. It does, however, incur an additional energy utilization cost relative to an equivalent system using a centralized architecture. Thus, the design directions of a long endurance science oriented AUV (which must be efficient with respect to energy consumption) run counter to the design directions of a flexible AUV (which needs modularity to ease science sensor maintenance).

Several design parameters have been derived to assist in dealing with this tradeoff issue: Energy Consumption, Control Architecture Topology, and Platform Flexibility.[6] The relationships among these parameters in terms of select AUVs are graphed qualitatively in Figure 3.

Since energy consumption is a paramount concern with a SUAV, it is graphed along the abscissa as the independent variable. The ordinate shows the relationship of increasing an AUV's flexibility by distributing its subsystems on an internal control network. Increasing the distributed nature of a system increases however its energy consumption (by increasing the count of energy consuming components).

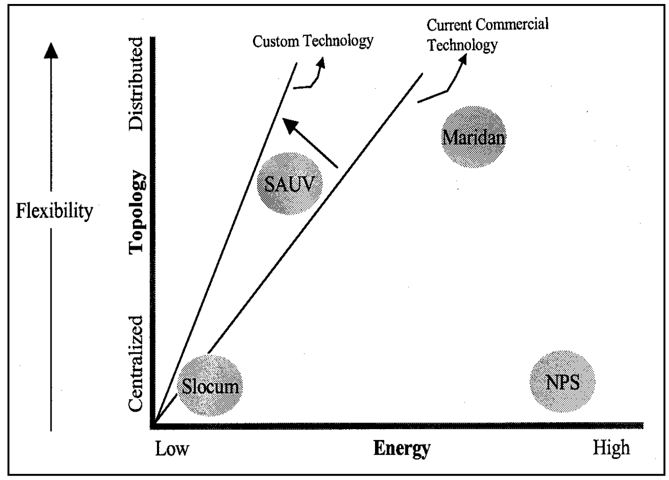


***Figure 3. AUV Design Drivers***

While long duration science missions demand the high flexibility and computation capability afforded by architectures employed in AUVs such as the Maridan Martin and the FAU Ocean Explorer, the energy cost of their hardware solutions is too high to work in a SAUV. In the effort to exploit those capabilities at lower energy cost, it was concluded that the SAUV could not directly utilize technology developed for the Martin/Ocean Explorer types of AUVs. Consequently, work was undertaken to arrive at a solution that would "push" the SAUV's position in the Figure through the "current commercial technology" boundary leftwards towards the "custom technology" curve.

Two major control networking systems utilized by other AUV workers were considered: LonWorks by Echelon Corp. and the open systems Controller Area Network (CAN). While both solutions provide the necessary bandwidth for AUV systems, CAN was selected for the SAUV due to energy cost, price, multiple vendor availability, and arbitration scheme.[8] The Martin also utilizes the CAN control bus, so the details of its solution were scrutinized. Driven by energy consumption concerns, it was decided to reduce the distributedness (node count) by designing a generic but expansible CAN based node.

Battery chemistry technologies were also researched and nickel metal hydride batteries were determined to be the best solution for SAUV use. They have little residual memory effect like the currently used nickel cadmium batteries and have better power density than lithium ion chemistry.[9]

***Common Control Language.*** Support development of a communication language for inter-platform command and control, also known as the Common Control Language (CCL).

*Results*. AUSI tested aspects of this CCL specifically related to relaying of vehicle status and capabilities during AUV Demo 99. In addition, AUSI is currently integrating a more complete set of the CCL into it's SAUV prototype vehicle.

## IMPACT/APPLICATIONS

The use of solar powered AUVs in the future will allow scientists and military investigators to perform missions of the sort which are unattainable at present. Solar AUVs will allow users to remotely conduct missions in which they can acquire significant data over vast areas of the ocean for long periods of time, and have access to the data and vehicle through communication on a daily basis. This is a significant first step in providing at sea satellites.

## TRANSITIONS

This technology should undergo a series of long endurance at sea trials in conjunction with scientists and/or military users to assist in the transition from technology development and assessment to commercial viability. Collaborations are being developed with industry and various scientific users.

## RELATED PROJECTS

This work has direct relevance to the Autonomous Ocean Sampling Network project since solar powered AUV's could well serve as autonomous agents within that network. Similarly the work on Cooperative Distributed Problem Solving for controlling AOSN (ONR #N00014-96-1-5009) is also being accomplished at AUSI and is relevant to this solar powered AUV system.

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